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Evolution of the dual-readout calorimeter

ALDO PENZO, on behalf of 4th Concept and DREAM
INFN-Sezione di Trieste, Area di Ricerca, Padriciano, Trieste, Italy
E-mail: aldo.penzo@ts.infn.it

Abstract. Measuring the energy of hadronic jets with high precision is essential at present and future colliders, in particular at ILC. The 4th concept design is built upon calorimetry criteria that result in the DREAM prototype, read-out via two different types of longitudinal fibers, scintillator and quartz respectively, and therefore capable of determining for each shower the corresponding electromagnetic fraction, thus eliminating the strong effect of fluctuations in this fraction on the overall energy resolution. In this respect, 4th is orthogonal to the other three concepts, which rely on particle flow analysis (PFA). The DREAM test-beam results hold promises for excellent performances, coupled with relatively simple construction and moderate costs, making such a solution an interesting alternative to the PFA paradigm. The next foreseen steps are to extend the dual-readout principle to homogeneous calorimeters (with the potential of achieving even better performances) and to tackle another source of fluctuation in hadronic showers, originating from binding energy losses in nuclear break-up (measuring neutrons of few MeV energy).

Keywords. International linear collider; dual readout; calorimetry.

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1. Introduction

One of the goals for ILC detectors is to reach jet energy resolution of $\sigma_E/E \approx 30\%/\sqrt{E}$ or better. It is generally believed that such energy resolution should be achieved through particle flow analysis (PFA) [1]. This implies fine segmentation of the calorimeters, with enormous numbers of channels ($\approx 10^8$) and consequently very large costs. The 4th concept design proposes a calorimeter system of a relatively simple construction and moderate costs, however with excellent properties, built upon experience gained with the extensively beam-tested DREAM (Dual REAdout Module) prototype. The main idea of multiple readout calorimetry is to independently measure for each hadronic shower those physical quantities that have large fluctuations and lead to large spread in energy response. The principal sources of fluctuations in hadron calorimetry are:

- spatial differences in the point-to-point distribution of energy deposition,
- fluctuations in the electromagnetic fraction, f_{em}, of hadronic showers,
- variations of the binding-energy losses in nuclear break-up processes.

The first can be dealt with by sampling the calorimeter with fibers at few millimeters' spacing, the second by directly measuring the (relativistic) soft electrons (a major component of the electromagnetic fraction in the shower) through the Cerenkov light produced in quartz fibers. Binding-energy losses can be monitored by detecting neutrons of energy close to 1 MeV in each shower. DREAM has used two different types of longitudinal fibers, scintillator and quartz respectively, viewed by separate PMT, to determine the electromagnetic part of each shower, obtaining already quite promising results in resolution, absolute scale and linearity [2].

Addition of a third (neutron-sensitive) fiber, would in principle allow suppression also of binding-energy fluctuations. As a part of the technical studies on the DREAM prototype, it has been shown that the scintillation and Cerenkov lights can be separated (by timing and/or directionality) even if produced in the same scintillator and read-out with the same PMT [3]. This would simplify the calorimeter structure and reduce readout costs, if the full pulse shape of the signals is properly analysed. At this stage, people involved in DREAM and 4th are engaged in a campaign of R&D and tests (with sources, cosmic rays and beams) throughout 2006 (and 2007) in order to firm-up the dual-readout principle, to extend it to homogeneous calorimeters (f.i. scintillating crystals, with a potential of even better performances) and to tackle the remaining source of fluctuation in hadronic showers, from binding-energy losses (measuring neutrons of few MeV energy).

2. The dual-readout module: DREAM

The DREAM prototype is a calorimeter module approximately 2 m long, and with an effective diameter close to 32 cm, weighing about 1.5 tons. It is made of 2 m long extruded square (4×4 mm^2) copper rods, with a hole 2.5 mm in diameter, containing 7 fibers (0.8 mm in diameter each): 3 scintillator and 4 quartz (or acrylic plastic) representing a basic cell. In total, there are 5580 copper rods (1130 kg) and 90 km of optical fibers. The relative volume composition is: Cu : S : Q : air = 69.3 : 9.4 : 12.6 : 8.7 (%) and filling and sampling fractions are 31.7% and 2.1% respectively. The effective radiation length is $X_0 = 20.1$ mm and the Moliere radius $R_{\rm M} = 20.35$ mm. The nuclear interaction length is $L_{\rm int} = 200$ mm, corresponding to 10 $L_{\rm int}$ total Cu depth. The effective radius is 162 mm (0.8 $L_{\rm int}$, 8 $R_{\rm M}$). 270 cells are arranged in a tower of hexagonal shape, there are 19 towers and the two types of fibers from each tower are read with two Hamamatsu R580 PMT, for a total of 38 PMT. This DREAM module was limited to 1-tonne of Cu due to funding constraints, and had a diameter insufficient to fully contain the hadronic showers. Thus its performance was limited by leakage fluctuations; however it gave demonstration that a dual readout calorimeter is feasible and offers several benefits.

3. DREAM performance

The results of the test runs in 2003 and 2004 (about one week each) showed that this dual-readout calorimeter has the following main features [2]:

- when corrections are applied for the $f_{\rm em}$ and leakage fluctuations, the energy resolution is excellent, about 20–25%/$\sqrt{E}$ for π's and 'jets';
- the response is Gaussian, to a good approximation; and,
- the response is linear in hadronic beam energy with a calorimeter calibrated with 40 GeV electrons (only) [4].

Of these three beneficial features, the third is probably the most important: such a detector can be calibrated at the Z^0 peak with 45 GeV $e^{\pm}$, $\mu^{\pm}$ and jets, and can be expected to measure with high precision the energies of particles and jets up to 500 GeV. Furthermore the dual readout calorimeter provides a unique identification of muons relative to pions with a background rejection of 10^3, or better, due to its separate measurements of ionization and radiative energy losses [5]. Besides these results specifically relevant to its calorimetric performance, other technical studies on the DREAM prototype, have shown the spatial distributions of Cerenkov and scintillation light in showers [6], as well as the separability of Cerenkov and scintillation light in a single optical medium [3].

4. New developments

The two partially overlapping communities of DREAM and 4th are carrying on intense R&D and test activities through 2006 and 2007, in order to confirm the dual-readout potential, to extend it to homogeneous calorimeters (scintillating crystals) and to implement measurements of neutrons with few MeV energy, in order to handle binding-energy losses, another source of fluctuation in hadronic showers. The plans and objectives for the R&D activities are described in various documents, aiming specifically at ILC [7] and more general [8]. Some of the tasks for the 4th concept design group are listed in [9]: these include construction of a cubic-meter dual-fiber readout module to overcome the leakage fluctuations that limited the performance of the 1-tonne DREAM module. When this module will be constructed (money issue!) it will also be a benchmark for the design criteria of a full-scale ILC multiple-readout calorimeter prototype. Meanwhile various R&D tasks will be performed:

Hadronic shower simulation: The development of sophisticated and high precision calorimeters will make stringent demands on hadronic shower simulation codes, starting with GEANT4 to augment the hadronic interaction parts of the code in order to successfully reproduce well-known results in several types of calorimeters that, to date, are still not simulated with full success. The GEANT4 package should be implemented to improve the simulation of some features of hadronic calorimetry: in particular, the known and well-measured electromagnetic fraction compensation mechanisms, neutron compensation mechanisms, electromagnetic content measurements, and the differences between pion and proton showers in highly non-compensating calorimeters.

Dual-readout crystal front section: Tests of $PbWO_4$ crystals for dual-readout of scintillation and Cerenkov light would provide enhanced photon yields with respect to quartz fibers and therefore better energy resolution. The small channel size will give spatial resolution on electrons and photons. The dual-readout will gain from these characteristics and achieve better hadronic energy resolution.

Neutron detection: Various methods can be applied to detect MeV neutrons from binding energy losses in nuclear processes:

1. *Time distribution*: Reading the fibers (scintillating a quartz) out to about 300 ns later than the initial particle impact, should allow us to catch the slow neutrons whose energy is roughly the binding energy losses in nuclear processes, approximately $T \sim 1$ MeV. The neutron velocity is $v \approx \sqrt{2T/M_n} \approx 0.05c$. For a mean neutron interaction length of several centimeters, the expanding neutron content produced by a showering jet will possibly fill about 0.5 m^3 over a few hundred ns.
2. *Loaded fibers*: We will test a third fiber as a specifically neutron sensing fiber, loaded with either Li or B: there are various plastic, glass or liquid scintillators loaded with appropriate neutron converters.
3. *Hydrogen-rich vs. hydrogen-free fibers or liquids*: The neutron signal might be found by the difference between the first and the second type of scintillators.
4. *Scintillators with different Birks' constants*: Scintillators sensitive to heavily ionizing slow protons, due to typical ionization quencing effects, might select np scattering.

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